Progress on the Active Alignment System for the IXO Mirrors

Mark D. Freeman*, Paul B. Reid, William Podgorski, David Caldwell
Smithsonian Astrophysical Observatory, 60 Garden St., Cambridge, MA USA 02138

ABSTRACT

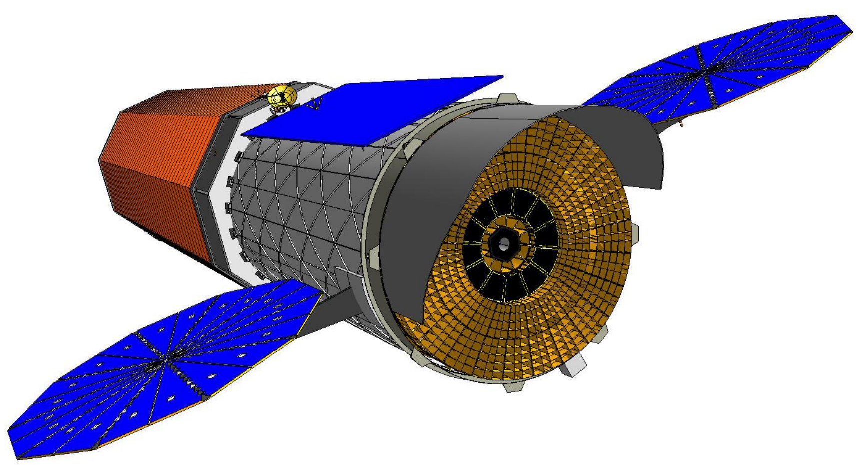
The next large x-ray astrophysics mission launched will likely include soft x-ray spectroscopy as a primary capability. A requirement to fulfill the science goals of such a mission is a large-area x-ray telescope focusing sufficient x-ray flux to perform high-resolution spectroscopy with reasonable observing times. The IXO soft x-ray telescope effort in the US is focused on a tightly nested, thin glass, segmented mirror design. Fabrication of the glass segments with the required surface accuracy is a fundamental challenge; equally challenging will be the alignment of the ~7000 secondary mirror segments with their corresponding primary mirrors, and co-alignment of the mirror pairs. We have developed a system to perform this alignment using a combination of a coordinate measuring machine (CMM) and a double-pass Hartmann test alignment system. We discuss the technique, its ability to correct low-order mirror errors, and results of a recent pair alignment including progress toward the required alignment accuracy of < 2 arcseconds. We then look forward toward its scalability to the task of building the IXO telescope.

Keywords: x-ray optics, mirror support systems, optical alignment, Hartmann test, IXO mission

1. INTRODUCTION

The success of the Chandra X-ray Observatory has led to the need for a large area x-ray spectroscopy mission. The International X-ray Observatory (IXO) is NASA's next priority in large x-ray astronomy missions. The 2000 Decadal Survey confirmed this, assigning it predecessor, Constellation-X (Con-X)[1][2], the second highest priority for large missions, behind only the James Webb Space Telescope. Con-X was designed to probe questions surrounding black holes and General Relativity, the origin and evolution of the universe, and further the search for dark energy and matter. Indeed, similar fundamental science goals have been the impetus for the Xeus mission proposed at that time by the European Space Agency (ESA) as their next major high-energy astrophysics platform. Common to both missions was a soft x-ray telescope with large collecting area and moderate imaging performance. Recently, NASA and ESA have signed a letter of agreement to pursue a joint mission called the International X-ray Observatory (IXO), merging the science goals and technologies.

The overall IXO mission is described in reference 3. In its most recent conception, IXO contains a single large soft X-ray Telescope (SXT) with a bandwidth of 0.25 to 12 keV, mounted in a single spacecraft and launched on an Atlas 551 or Ariane V. It will provide an effective area that exceeds the fundamental mission requirement of 3 m^2 at 1.25 keV and 0.65 m^2 at 6 keV, while maintaining imaging performance of 5 arcsec (2 arcsec goal) for energies less that 7 keV. To accomplish this, two technologies are being pursued to meet the science requirements. The ESA-led technology features stacked, etched silicon “plates” which are



* email: mfreeman@cfa.harvard.edu phone: (617)495-7106

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formed to provide focusing X-ray optics (described in several other papers in this conference). The NASA effort is a continuation of the Con-X optics development, which has concentrated on the use of thin glass elements, formed by high-temperature slumping on precision mandrels to near-net shape, and then aligning these lightweight elements as pairs and co-aligning the pairs in a modular fashion.

The conceptual SXT mirror assembly is divided into segments, both radially and azimuthally. The current 3.2m diameter SXT design has twelve 30° azimuthal segments in an inner ring, surrounded by middle and outer rings of twenty-four 15° segment modules. With primary and secondary mirror modules containing around 100 thermally formed ("slumped") mirror segments each, a total of ~14,000 glass segments must be mounted in the SXT with optical precision whilst supported sufficiently well to withstand the rigors of launch.

This module-based approach to supporting mirror segments (reference [4]) must allow for precision alignment while maintaining a common focus for all segments, and do so without disturbing the precision optical design of the individual slumped segments. It can be seen in Figure that the modular structure allows for the possibility of holding the segments either on their ends (axially fore and aft) or along their (azimuthal) edges. Both schemes have been used for various mount concepts and alignment approaches. In this paper we describe the development of an alignment technique that constrains the mirror at five points along the fore and aft ends of each segment. During the alignment process, we use both a coordinate measuring machine (CMM) and an optical Shack-Hartmann tester called the Centroid Detector Assembly (CDA) to manipulate the constrained points to align the mirror segment. In addition, we present results of a recent alignment of a mirror pair and discuss the progress of the technique toward meeting the mission alignment goals.

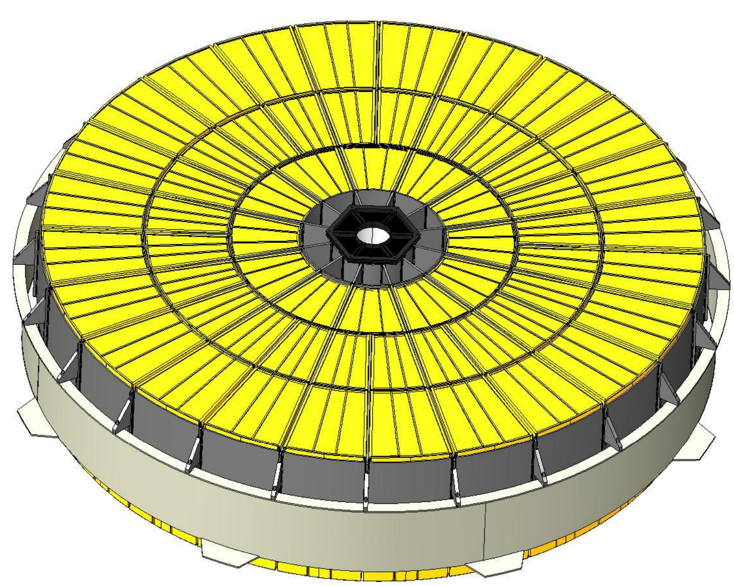

Figure 1. Conceptual SXT telescope assembly.

2. PROCEDURE FOR THE ALIGNMENT OF A MIRROR PAIR

The Constellation-X and now the NASA IXO mission concepts, despite many configuration variations, have consistently included SXTs with thin glass segments[5] assembled in a modular structure. Although the exact size and angular span of the modules have gone through several iterations, there have been two fundamental guidelines that derive from the slumping process that have limited the module size and span to a manageable range: (1) Limits on forming mandrel size and the slumping process itself have driven the project toward a consistent segment length of approximately 200mm, and (2) The selected glass (Schott D263) is readily available in sheet widths of 400mm. Various assembly schemes have been proposed that hold the glass on ends or edges whose prime motivation has been alignment of the mirror segments. One of the most enduring concepts consists of formed glass segments are held at a discrete number of points on both the fore and aft ends of each segment, where these points are manipulated precisely to align the mirror segments. In this section, we describe this process and the required hardware to align a pair (primary and secondary reflectors) of Wolter-I optical elements that provides the means to meet all the relevant alignment requirements.

2.1 The Process Concept

The process begins with precise knowledge of the shape of the glass segments. Ideally, the segments would conform exactly to the optical prescription for the particular mirror pair being aligned, and one goal of the forming process is to make the segments meet the alignment process requirements. Since the forming process is still being developed, and the mirror parameters that are the most difficult to measure precisely (average radius, cone angle) are the most critical to the

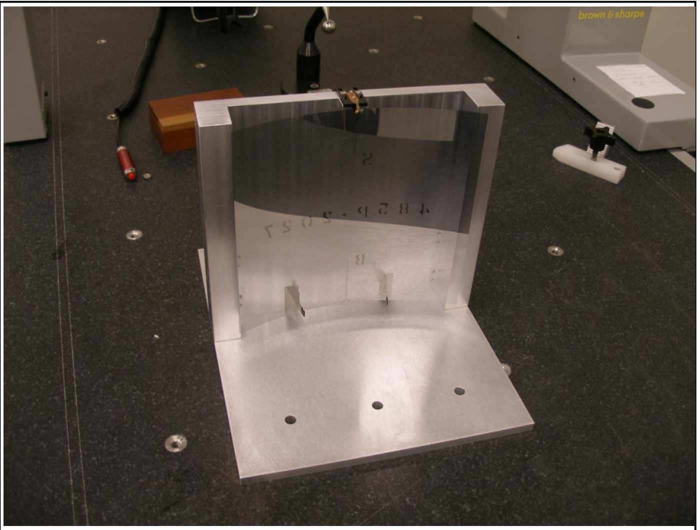

Figure 2. Metrology mount for CMM measurement of "free" mirror segments

alignment process, we begin by measuring the optics on a metrology mount. To minimize the gravity deflection of the unsupported segment, the measurement is performed with the glass segment vertical, as shown if Figure 2. We use a coordinate measuring machine (CMM) to measure and map the optical surface in 3 dimensions. To reduce error and gravity effects, we measure each glass segment with the wide (larger radius) end both at the top and the bottom. Both datasets are input data to "FitCone", a program developed by Bauer Assoc. to determine the best-fit cone to the surface and its relationship to the mirror edges. The results of the two are averaged and, combining the measurements for both the primary and secondary segments, we determine the best alignment for the pair which also minimizing shape changes, which, if sufficiently large, would require the application of enough force to distort the higher-order shape of the segment.

Once the alignment parameters are determined, the primary mirror is placed in a stiff housing, resting on an adjustable two-point support with the wide end down (Figure 3). Precision adjusters and bonding rails are then affixed to the mirror at 5 points along the top (narrow end). The CMM is used to adjust the bottom support to correct both pitch and yaw tilts. The five top adjusters are then positioned to form the narrow-end radius determined from the alignment optimization. Once correctly positioned, the five points are bonded to radial "rails". The assembly is then inverted and the adjustable support removed and replaced by five adjusters at the same azimuthal angular locations as used previously. These are then likewise adjusted to make any minor correction to pitch and set the wide-end radius (to CMM accuracy).

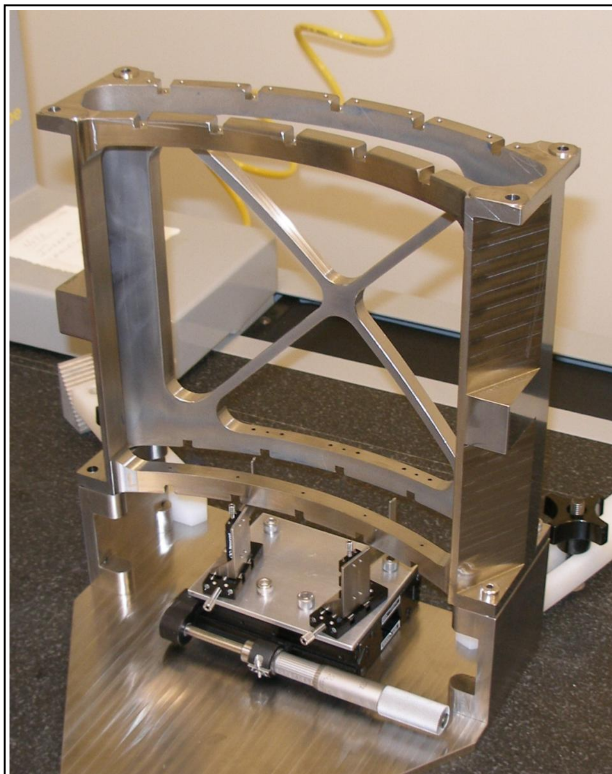

Figure 3. Housing with adjustable mirror support

The entire assembly, with adjusters still attached and holding the wide end of the optic, is bolted to a precision mount and placed in the optical alignment system or Centroid Detector Assembly (CDA) [Fig. 4]. This system is a double-pass Shack-Hartmann test, wherein a laser source, placed at the nominal optic focus, is steered to n discrete points on the optic surface, passed through an aperture plate to limit beam size, and returned using a precision flat via the same path to a quad-cell detector coincident with the laser source. Based on the position of return spots produced by scanning around the mirror azimuth, the five adjusters are positioned to optimize the mirror alignment (focus and coma) and minimize residuals (higher-order errors). Upon achieving proper alignment with minimum residuals, the five points on the wide end of the primary are bonded to the support rails.

The secondary mirror is then aligned to a separate housing in a similar manner; however, the narrow end of the secondary segment is placed on the adjustable supports, and the five adjusters and rails are placed on the top (wide end). The mirror placement and wide end radius are then adjusted using the CMM, and the wide end is bonded to the rails.

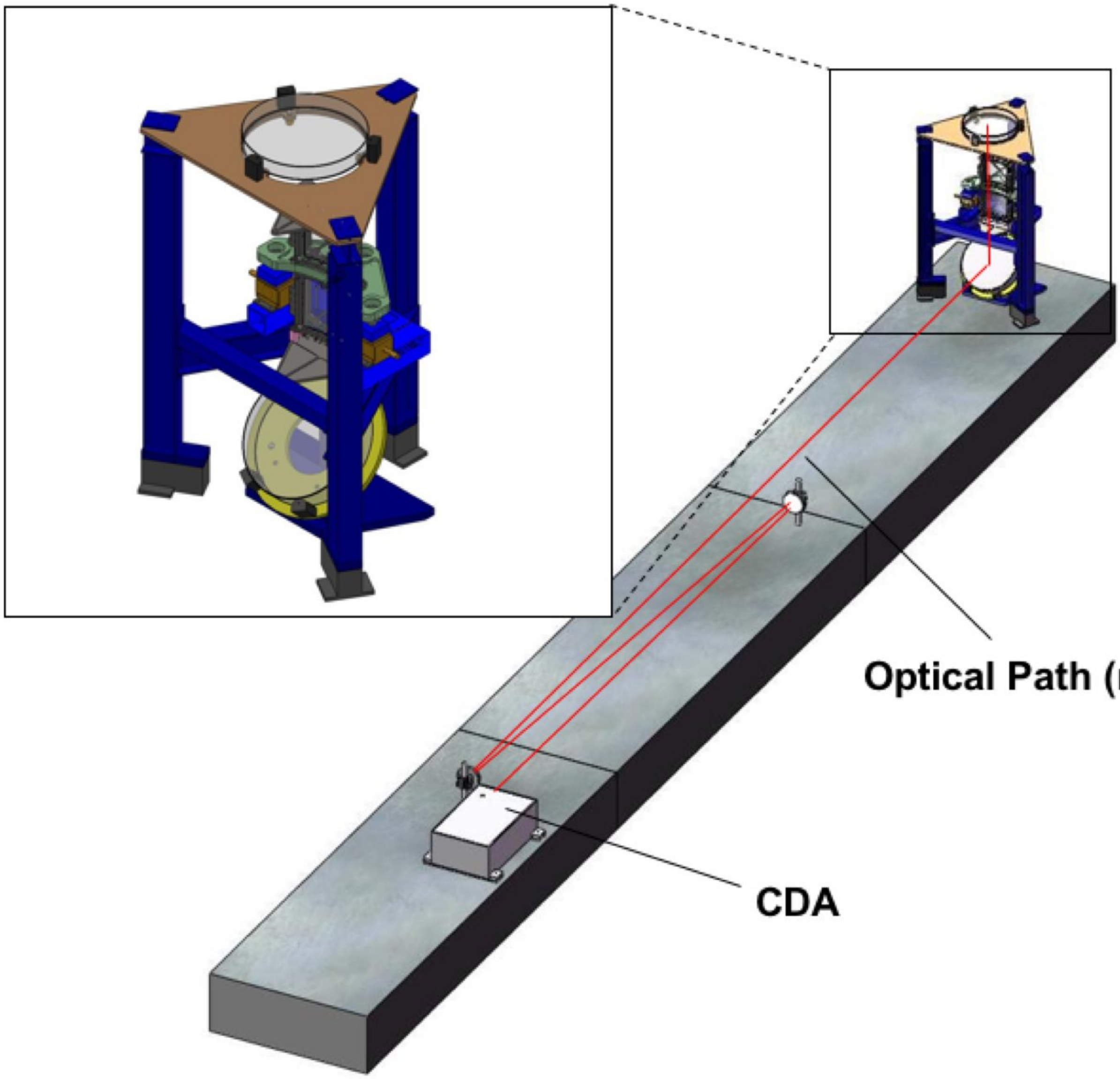

Figure 4. The optical setup of the Centroid Detector Assembly (CDA). Supported by set of optical tables, the system consists of the CDA with a laser source; the beam is folded to produce sufficient focal length and then vertically to pass through the optics assembly and reflected off a retro-flat positioned at the top of the tower. The return beam's position is measured by a quad cell detector coincident with the laser source in the CDA.

The secondary segment assembly is then bolted to the underside of the precision support plate, using CMM measurements to align the secondary to the primary, principally to make the optical axes of the two segments coincide by adjusting decenter and relative tilt between the pair. The "roughly" aligned mirror pair is then placed in the CDA optical test setup (with the focal length halved due to the introduction of the secondary mirror) and aligned. Rigid body tilt adjustments are performed first, based on deconvolution of the Hartmann spot pattern; this is done to minimize strains on the mirror introduced by adjuster motions. Once minimized, the five actuators are adjusted to minimize remaining tilt errors and reduce the higher-order residual errors. The five points are then bonded in position, producing an aligned and bonded mirror pair. shows an aligned and bonded mirror pair in the CDA optical tower.

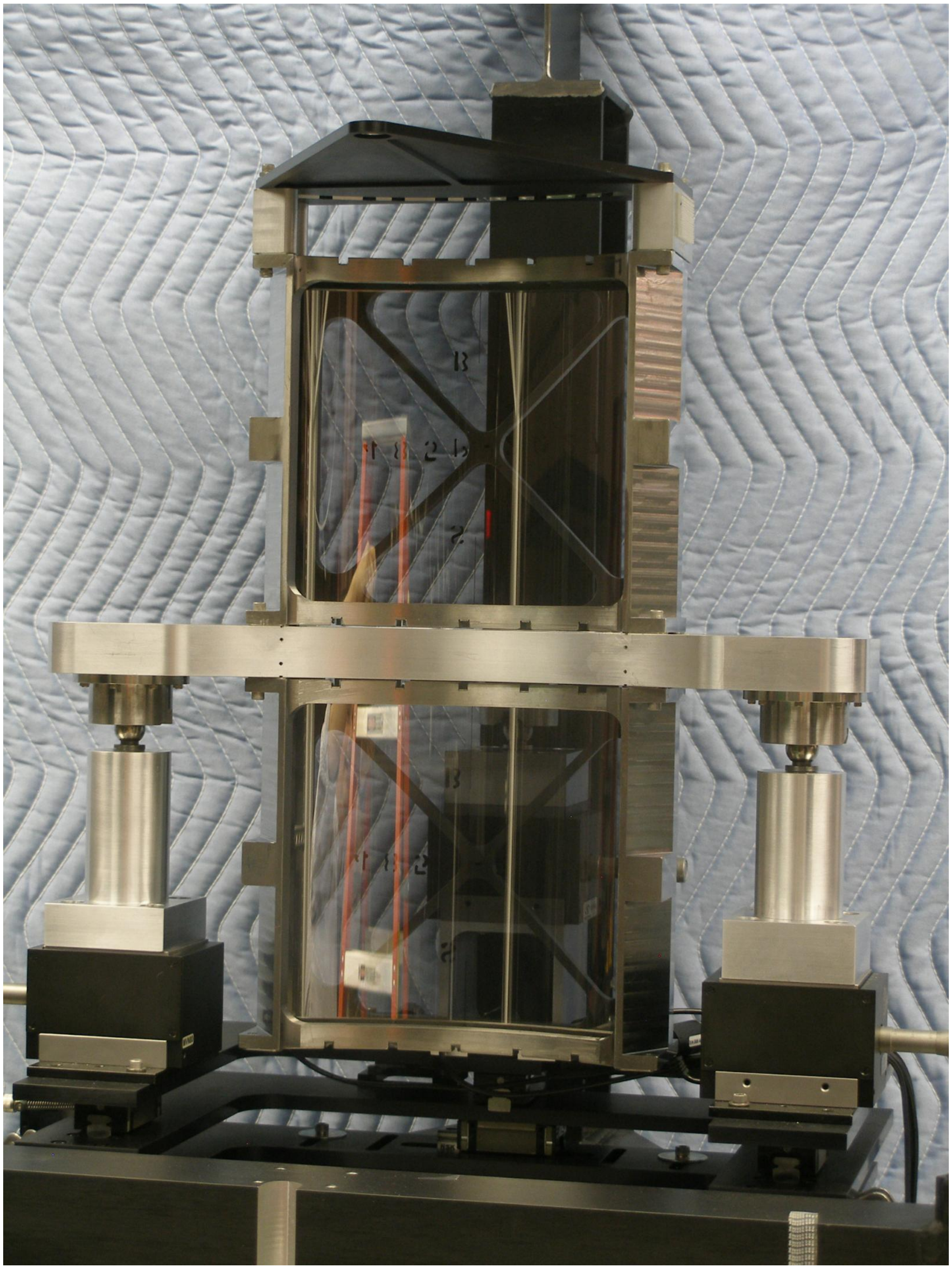

Figure 5. An aligned and bonded mirror pair in the CDA optical tower. The central mount place rests semi-kinematically on hardened balls (at top of large aluminum stanchions).

3. ALIGNMENT RESULTS FOR A REPRESENTATIVE MIRROR PAIR

In this section we present alignment results for a specific primary/secondary pair of segments, formed as described earlier by NASA/GSFC. The pair are identified as 485P/S-2027; the first number, 485, refers to the average diameter of the mirror segment, the P/S refers to the primary/secondary segments, and the last (2027) is serialization.

3.1 Freestanding mirror measurements

The 485P/S-2027 primary and secondary mirror segments were produced together in a single slumping run, and full segment metrology was performed at GSFC using a Fizeau interferometer and a cylindrical null lens to convert the plane wave to a cylindrical wave[6]. These data are shown in Figure 6.

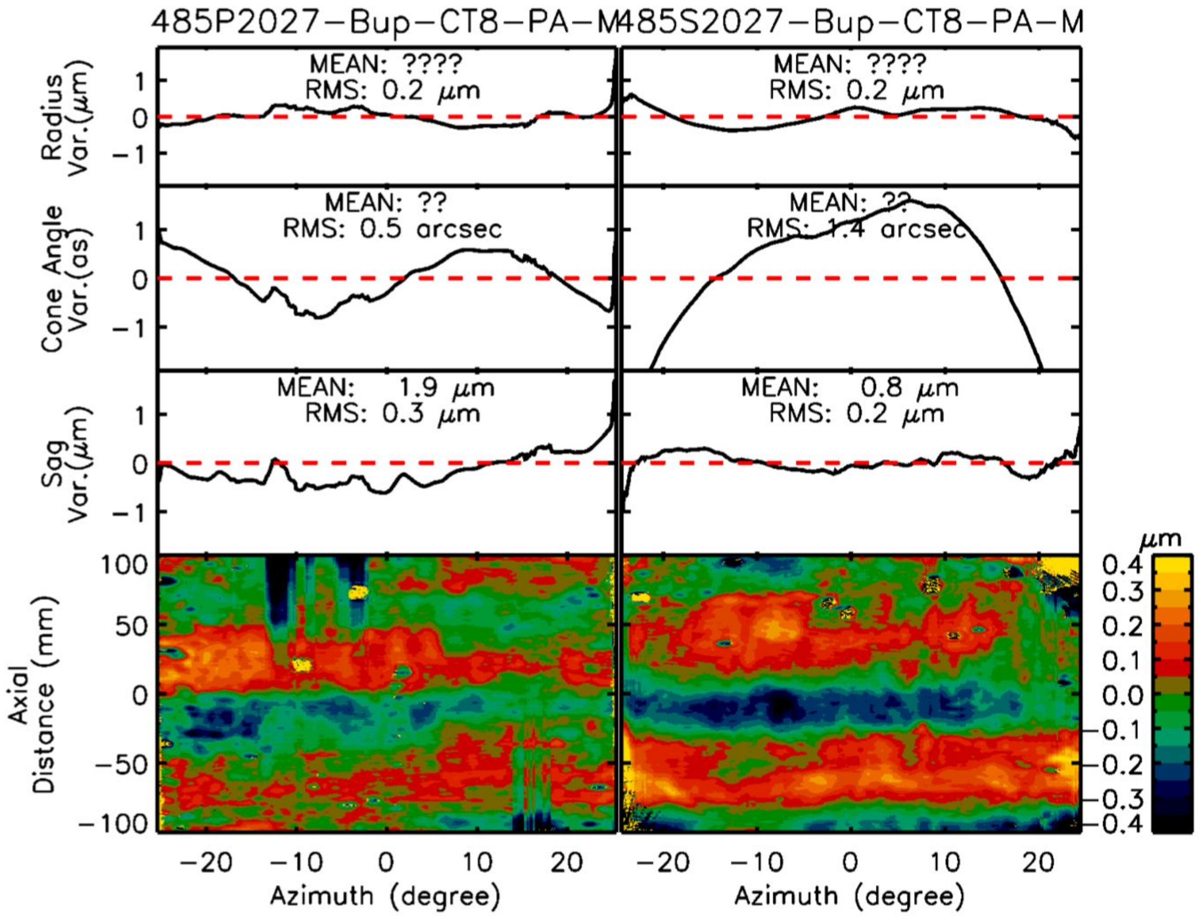

Figure 6. Interferometry data from GSFC freestanding measurement. Note that the mean radius and cone angle, the more critical measurement values for the *alignment* process, are not captured in the interferometric measurements. SAO makes these measurements using a CMM as described in Section 2.1.

The interferometry data confer that for this mirror pair, if mounted and aligned strain-free, would produce an approximately 14 arcsec HPD in x-ray test, far from the 5 arcsec requirement, primarily due to mandrel figure errors (low- to mid-spatial frequency) and slumping details (mid-spatial frequency); ongoing improvements to this portion of the process are discussed in another paper in this conference. These are generally of higher order than can be measured by the Hartmann test; sag (second-order) and higher-order axial terms are not measurable due to the centroiding of the full-axial-length illumination of the mirror. However, with 14 points measured around the 50° segment, low-order azimuthal variations, especially cone angle variation (second pair of plots) do register in the Hartmann tests. We compute that this mirror pair, mounted strain-free in our test setup, would produce a ~6 arcsec RMS diameter spot (~4 arcsec HPD assuming a Gaussian distribution) due to these errors. **Note: From this point forward in this paper, we will use RMS diameter [RMSD] as the alignment performance metric, since in general the alignment spot distributions are highly non-Gaussian**.

As mentioned earlier, the first step in the process is to measure the conic parameters of both mirrors in the free state, to determine an optimal alignment condition, essentially matching radii with minimum strain imparted to either mirror. To obtain the input data, the reflective surface is measured with a 20 point axial (~every 10 mm) by 48 point azimuthal (every degree) grid. The FitCone parameters for the mirrors are given in Table 1. The wide-end down (WED) and narrow-end down (NED) data are averaged, and an optimum set of radii is determined for both segments.

Table1. Data from freestanding CMM measurements of 485P/S-2027, fitted using FitCone. WED indicates Wide-end Down measurement; NED indicates Narrow-end Down. Note that due to the inversion of the mirror, the Z-0 (bottom of the mirror) flips between the wide and narrow ends, and the sign of the semi-cone angle inverts.

Segment/Orientation	485P-2027 WED	485P-2027 NED	485S-2027 WED	485S-2027 NED
Cone radius at z=0 plane	244.1323	242.8900	242.0782	238.0023
Semi-cone angle (degrees)	-0.4241	0.4032	-1.1997	1.2132
Cone axis tilt about x (degrees)	0.0174	-0.0321	-0.0710	-0.0779
Cone axis tilt about y (degrees)	0.7383	-0.1387	1.4711	-0.9093
RMS deviation from best fit cone	0.0012	0.0010	0.0015	0.0011
RMS dev. from best fit 2nd order	0.0010	0.0009	0.0015	0.0011
Best fit outward sag (ctr - ends)	0.0015	0.0017	0.0007	0.0010
Wide End Radius	**244.1323**	**244.2974**	**242.0782**	**242.2374**
Narrow End Radius	**242.6518**	**242.8900**	**237.8900**	**238.0023**

3.2 Primary Alignment

The primary is then placed in the housing on the adjustable support, with the top loosely held at the center point, and the CMM is used to determine a reference coordinate system for the housing based on specific machined housing surfaces. The supports are moved to center the mirror in the housing with the optical axis vertical. The five bonding rails and 5 "nano-adjusters" (so-called due to a 7 nm resolution element) are affixed to the housing. The wires from the adjusters are bonded to the mirror at the 5 points in this "free" state, and the temporary center holder is removed. The adjusters are then moved to set the primary narrow-end radius to its calculated best-fit value, and the mirror is bonded to the rails at these 5 points and the epoxy is allowed to cure (3 days). At this point the wires between the segment and the adjusters are cut and the adjusters are removed. To determine whether any of these operations have an effect on the segment position, we performed a CMM scan along the top edge after each operation (Figure 7). No significant deviations were seen after cutting the wires (to the CMM accuracy of about 0.7µm RMS – red curve); a small shift was seen when the actuators were removed (brown). Re-measurement of the housing to reestablish the coordinate system placed the data within measurement error of the earlier runs (blue), indicating that the actuator weight (they are cantilevered off the top surface) shifts the housing position slightly. The housing is then inverted, mounted to the optical alignment plate, the adjustable support removed, the five rails and adjusters are put in position over the wide end, and the wires attached. The coordinate system is reestablished for the inverted position, and the pitch and best wide-end radius are then similarly set by actuator adjustment.

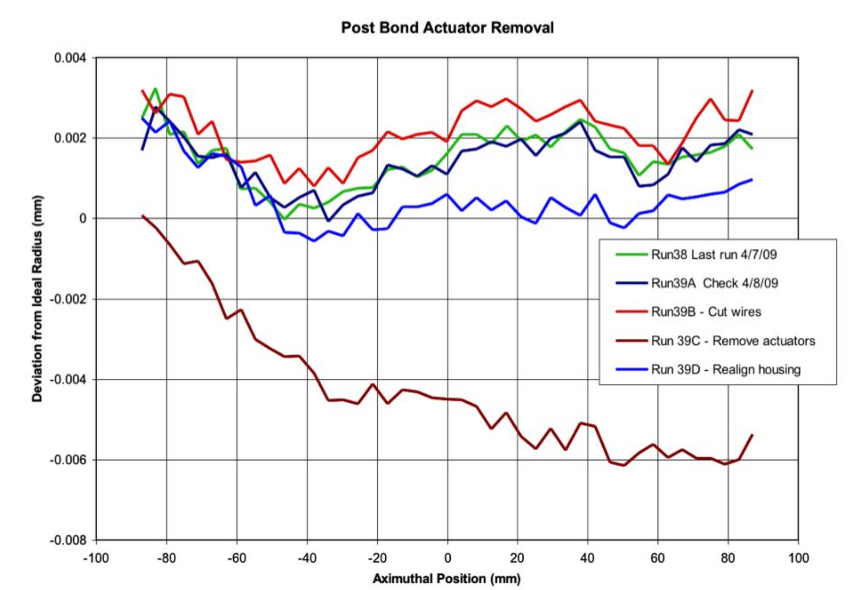

Figure 7. CMM data showing stability of the 485P-2027 segment narrow end during actuator removal

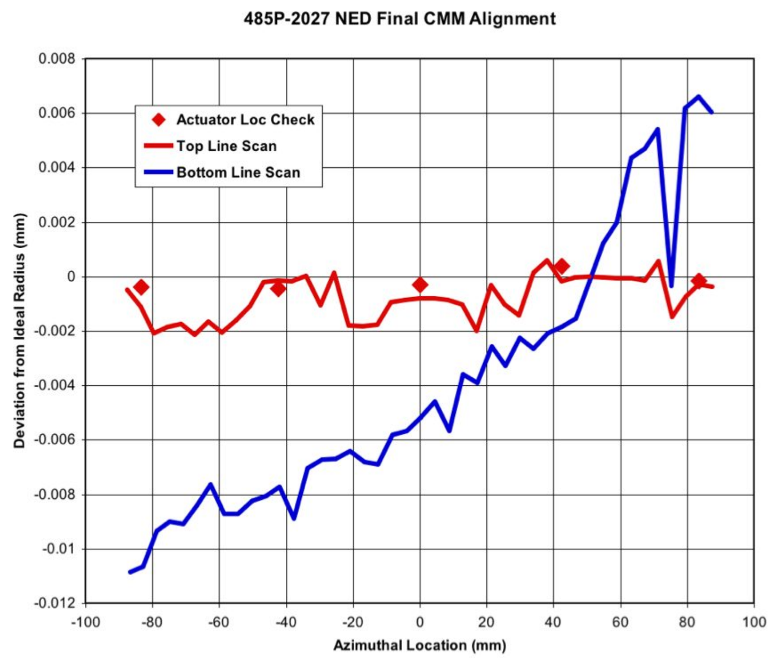

Figure 8. CMM scans showing deviation from the ideal radius near the top and bottom edges of the 2027 primary.

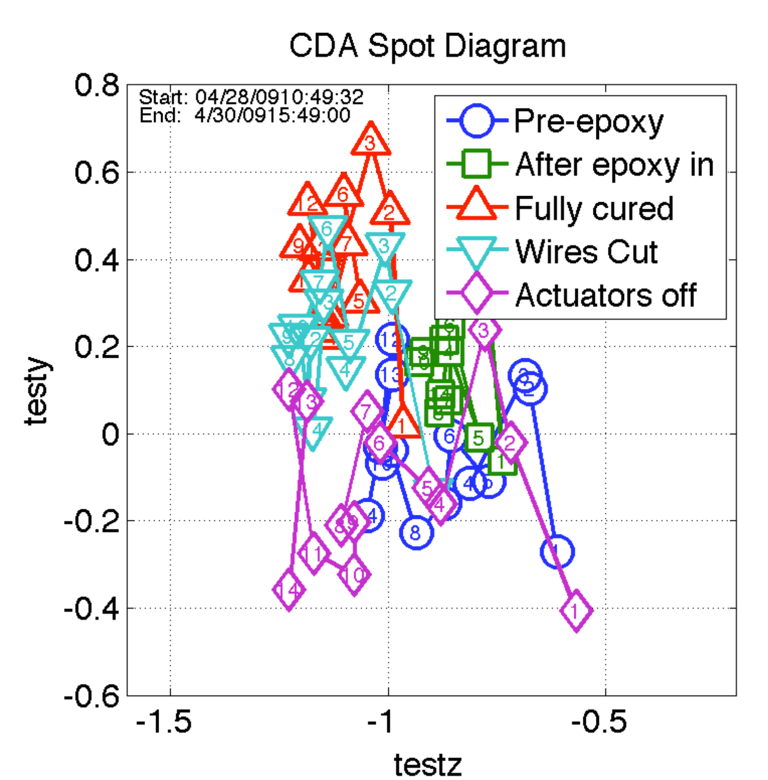

Figure 9. CDA spot diagrams of the alignment state of 485P-2027 before insertion of the epoxy (blue), after insertion (green), full cure of the epoxy (red), separation from actuators (turquoise), and after the actuators are removed from the housing (violet).

Figure 8 is a plot of the data for the final CMM measurements of the 2027 primary mirror segment. Measurements at the actuator positions were taken first (red diamonds) to confirm correct adjustment, and then a final scan along the top (red) and bottom (blue) of the segment was made. There are several things to note in these data: (1) The actuator position measurements and the line scan agree to CMM precision at the actuator locations, (2) the sharp dip around +75mm in the bottom scan is an actual "dimple" in the optic at that location, produced during the slumping, and (3) the "tilt" in the bottom scan is due to a lateral offset of the coordinate system when the housing was inverted. Since final alignment is performed in the CDA system, we decided at the time not to correct this. Subsequent work has shown that it is worthwhile to make such corrections in the CMM to make the optical alignment process easier; we now match top and bottom curves to CMM measurement accuracy.

The P mirror in its housing is then taken to the CDA optical alignment system for final alignment. The three semi-kinematic supports in the tower have vertical adjustment, allowing the entire assembly to be tilted in both axes. This is done to bring the mirror into the best alignment possible without actuator motion. Once the best rigid body alignment has been achieved (based on deconvolution of the Hartmann pattern, see reference [5]), the actuators are used to minimize the spot size.

Once the best alignment state has been achieved, epoxy used to bond the mirror segment at the adjuster locations to the radial rails. Much effort and several revisions of the hardware design have resulted in the ability to retain the alignment state through application of epoxy and removal of the actuators. Figure 9 is a plot of 5 CDA measurements taken throughout the alignment and cure cycle. The first four, representing the "final" alignment before bonding, just after the epoxy is inserted, fully cured (3 days later), and after the actuators are disconnected, have RMS diameters between 2.0 and 2.45 arcseconds. In the final plot (violet), after the actuators have been removed, spot size

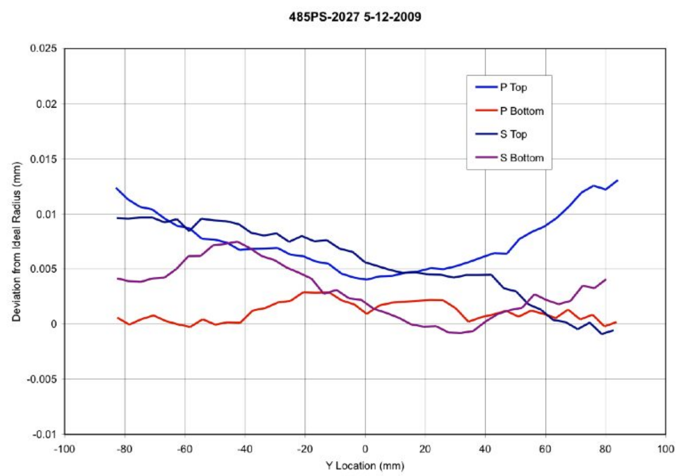

Figure 10. CMM measurements of the 485P/S-2027 pair at the top and bottom of each mirror segment. Measurements are subtracted from the calculated “ideal” radius for each segment at the location measured, based on initial freestanding measurements of the glass segment.

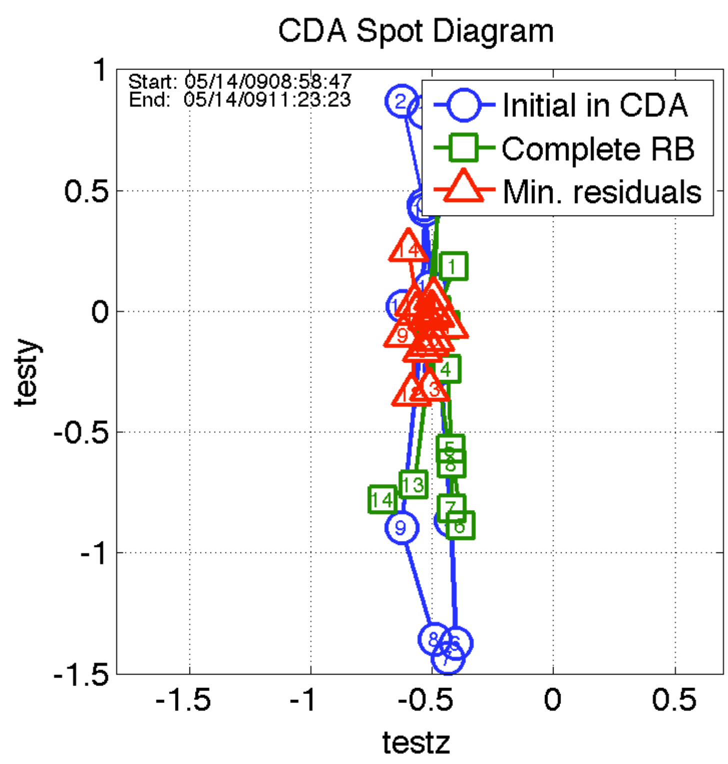

Figure 11. The 485P/S-2027 pair measured using the CDA. Blue curve is alignment as installed in CDA setup (18.9 arcsec RMSD); green curve is after basic rigid body corrections (12.8 arcsec RMSD); red curve is after minimization of residuals (3.7 arcsec RMSD).

has degraded to 3.31 arcsec. We believe this to be a combination of a slight housing flex due to removal of the cantilevered load of the actuators, and a temperature sensitivity of the bonded assembly due to a CTE mismatch between the mirror housing (Ti-6Al-4V) and the mounting plate (6061-T6 aluminum).

3.3 Mirror Pair Alignment

The procedure to mount the secondary is quite similar to that of the primary. The narrow end of the mirror segment is set on the adjustable support in the housing, and the five rails and actuators are attached to the top end, along with a temporary center adjuster. This adjuster and the bottom support are moved to position the top and bottom radii correctly within the housing using the CMM. The five actuator wires are then bonded to the segment, and any [small] radius corrections are made, iterating CMM measurements and actuator motions. The segment is then bonded in the five locations to the rails and the epoxy allowed to cure.

Rough alignment of the narrow end is also similar to the P-only alignment: the rails and actuators are attached, and the rough radius of the five points is set using CMM measurement. At this point, however, the procedure diverges. The housing is now mounted to the other side of the plate to which the P housing (with its bonded segment) is mounted. The CMM is then set to reference the P-housing for all measurements of the assembly. The four critical radii (top and bottom of both segments) are then scanned, and the S-housing is aligned in 5 degrees of freedom (all except distance from the P-housing, also known as despace, which is fixed) to place the 4 radii such that the optical axes of the two segments are correctly aligned. The CMM data for the 2027 pair in this rough aligned state is shown in Figure 10.

The assembly is then taken to the CDA setup, which has been reset to the focal length appropriate for the mirror pair (8.4m, for these segments) and aligned optically. Since the mirrors are fixed together at the plate, and the optical system is now two-bounce, rigid body alignments are relative (primary to secondary). Initial optical measurements and decomposition into the relative tilts determines whether or not shimming is necessary to achieve a reasonable starting point for fine adjustments with the actuators. If necessary, the pair is removed, shimmed, re-measured in the CMM, and returned to the CDA (done once for this particular pair). Once alignment can be achieved with sufficiently small actuator motions (currently targeted for 25 microns or less, TBR), we perform the actuator adjustments to trim the tilt for the best compromise of one-theta (focal length), two-theta (coma) errors, and higher-order errors to produce the minimum spot size. Figure 11 shows the progression of CDA measurements for the 2027 pair.

In this case, the spot size for the pair is only slightly larger than the result for the P-mirror alone. Indeed, despite relatively large and out-of-phase cone-angle variation errors for this mirror pair that as mentioned earlier would produce an approximately 6 arcsec RMSD spot, we achieved 3.7 arcsec RMSD. Although not fully separable contributors, we estimate that we have (1) achieved pair alignment approaching, if not fully achieving, the 1.5 arcsec RMSD error budget requirement, and (2) reduced low order cone-angle variation errors by roughly half.

4. LESSONS LEARNED

Several significant lessons were learned as we progressed through the alignment of this pair. Some major ones:

- The mirror segments cannot be "gripped" or similarly held without imposing moments or azimuthal loads that significantly affect mirror shape. Release of these forces/moments after the mirror is bonded in place produces shape and alignment changes too large to meet error budget requirements.
- Similarly, if the mirror is not bonded directly in the adjuster load path, release of the adjusters from the mirror segment produces unacceptable motions.
- Friction is the most significant contributor to positional changes through the bonding process. If the mirror is held radially but otherwise constrained only by small, fully elastic loads at the adjustment points (the wires from the actuators to the mirror serve as flexures in this regard), it may move slightly due to introduction of the epoxy, but will return (slowly, due to epoxy viscosity) to the correct position.
- Although it may be possible when the mirror production issues have been minimized, currently we cannot force the mirror to its design radius, nor can we fully bond one mirror end and subsequently adjust the other. This results in forces at the mount points that are large enough that we create unacceptably large changes in the higher-order figure of the mirrors, particularly sag.

In addition, we have made many procedural and hardware changes that make the process more straightforward. Among these are a significant improvement to the central plate that mounts both housings: It is now Ti-6Al-4V to match the CTE of the housings, and has been divided such that there is a sub-plate to mount the secondary mirror, with adjusters to improve rigid-body alignment between the primary and secondary during both the rough and final alignment stages. We have improved several aspects of the bonding procedure to minimize the impact on alignment and mirror shape.

5. CONCLUSIONS AND PLANNED FUTURE WORK

The alignment of thin-glass segments has progressed significantly. We have achieved alignment of a pair that approaches the alignment requirement of less than 2 arcsec RMSD, in a flight-like housing. There are no significant technical hurdles to applying the technique to the hundreds of shells in the flight mirror assembly module. We have shown the process to be largely deterministic, and with this or similar hardware and fairly simple software, the process could be automated, which may be key to producing a realistic schedule for flight mirror production.

We plan to repeat the process with a mirror pair with somewhat better characteristics relative to alignment. The intent is to show that the process is repeatable, and because the next pair has smaller low-order errors, the determination of the pure alignment value achieved should be more straightforward. Following that, and depending on progress in mirror production, we hope to receive a pair with much smaller sag and mid-frequency errors, such that an x-ray test could be performed on the aligned pair that would both confirm the alignment result and provide direct x-ray measurement of our progress toward the 5 arcsec HPD mission requirement.

We also plan to make the hardware changes necessary (mostly in the bonding rail design) to accommodate multiple pairs in these same housings. Achievement of the alignment requirements for multiple pairs in a flight-like housing, and maintenance of this state through representative environmental tests (vibration, thermal) would bring this portion of the process to Technical Readiness Level 6 (TRL-6), and retire one of the significant technical challenges of the mission. We plan to achieve this milestone by December 2011.

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REFERENCES

[1] N.E. White and H. Tananbaum, “Constellation-X Mission: Science Objectives and implementation Plan”, SPIE Proc., vol. **4851**, 293 (2003).

[2] R. Petre, *et al.*, “Constellation-X Spectroscopy X-ray Telescope (SXT)”, SPIE Proc., vol. **4851**, 433 (2003).

[3] David Robinson, Ryan McClelland, “Mechanical Overview of the International X-Ray Observatory”, IEEE Aerospace Conference, IEEEAC paper **1580**, March 2009.

[4] Ryan McClelland, David Robinson, Michael D. Hill, “Design concept for the International X-Ray Observatory Flight Mirror Assembly”, Paper **7437-7**, *to be presented at this conference*.

[5] J. Lehan, *et al.,* “Metrology for the International X-ray Observatory's soft x-ray telescope: mirrors and mandrels”, Paper **7437-24**, *to be presented at this conference*.

[6] William Zhang, David Content, Stephen Henderson, John Lehan, Robert Petre, Timo Saha, Stephen O’Dell, William Jones, William Podgorski, and Paul Reid, “Development of Lightweight X-Ray Mirrors for the Constellation-X Mission”, SPIE Proc. **5488**, 820 (2004).

[7] Paul B. Reid, *et al.*, “A comparison of different alignment approaches for the segmented grazing incidence mirrors on Constellation-X,” SPIE Proc. **7011**, 701111 (2008).